

Observational studies of stellar black hole binaries and ULXs

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Abstract

We outline a framework for understanding the X-ray spectra of high mass accretion rate stellar black holes based on X-ray data from RXTE and ASCA. Three spectral regimes can be separated out by the behaviour of the observed disk luminosity and temperature. The well established "standard regime" is seen when the disk dominates the spectrum, where only a small fraction of the luminosity is emitted in the power law tail. These spectra generally satisfy the standard relation expected for thermal emission from a constant area, namely that the disk bolometric luminosity, L_{disk} , is proportional to its maximum temperature, T_{in}^4 . However, at higher luminosities this starts to change to $\propto T_{\text{in}}^2$. This "apparently standard regime" is still dominated by the disk emission, but this difference luminosity-temperature relation and subtle changes in spectral shape may show that another cooling process is required in addition to radiative cooling. At intermediate luminosities there is an anomalous regime (or weak very high state) where the disk temperature and luminosity are less clearly related. These spectra are characterized by the presence of a much stronger comptonized tail indicating high energy electrons. When observed disk emission is corrected for the the effects of comptonisation then these points lie back on the standard relation. The growth of this comptonising corona is also clearly linked to the quasi-periodic oscillations, as these are observed preferentially in the anomalous regime. This presented picture was found to explain the spectral behavior of both black hole binaries in our Galaxy and LMC. Spectral evolution of several bright ULXs observed with ASCA were also successfully explained in the same picture.

Key words:

Black holes; accretion disk.

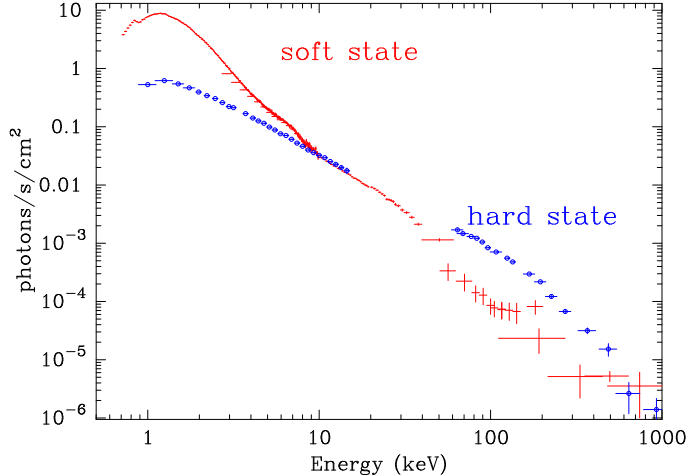


Fig. 1. X/ γ -ray spectra of Cyg X-1 in both the high/soft and the low/hard state, taken from Cui et al. (1998), Gierlinski et al. (1997), Balucinska & Hasinger (1991), Philips et al. (1996), and McConnell et al. (1994).

1 Classical understanding of stellar black holes in high accretion rate state

In a close binary consisting of a stellar-mass black hole and a mass donating normal star, the accreting matter releases its gravitational energy as X-ray radiation. In Fig. 1, we show two typical X-ray spectra of Cyg X-1, the best studied black hole binary, showing its two distinct spectral states. In the low/hard state, its spectrum is approximately a power-law, with an exponential cut-off near ~ 100 keV. By contrast, the high/soft state is characterized by dominant soft emission below 10 keV, accompanied by a hard power-law tail extending to 500 keV and beyond.

As described, e.g., by Makishima et al. (1986), the soft spectral component is interpreted as thermal emission from an optically thick accretion disk around the black hole, as it can be well reproduced by a multi-color disk model (MCD model; Mitsuda et al. 1984). This model approximates a spectrum from a standard accretion disk (Shakura & Sunyaev 1973). Under this standard disk solution, the Keplerian rotational energy takes up half of the gravitational energy, while the remaining half is radiated as approximately blackbody emission from the disk surface. The MCD model ignores any inner disc boundary condition, describing the disk local temperature $T(r)$ as

$$T(r) = T_{\text{in}} \cdot \left(\frac{r}{r_{\text{in}}} \right)^{-3/4}, \quad (1)$$

where T_{in} and r_{in} are the two spectral parameters of the MCD model, the maximum observed disk temperature and the apparent disk inner radius, re-

spectively. The latter is related to the true inner radius, R_{in} by

$$R_{\text{in}} = \kappa^2 \cdot \xi \cdot r_{\text{in}} \quad , \quad (2)$$

where $\xi = 0.41$ is a correction to account for a stress free inner boundary condition (Kubota et al. 1998) and $\kappa \sim 1.7\text{--}2.0$ is a colour temperature correction factor to account for distortions of the spectrum from a true blackbody (Shimura & Takahara 1995). The disk bolometric luminosity L_{disk} can be related to these two spectral parameters as

$$L_{\text{disk}} = 4\pi r_{\text{in}}^2 \sigma T_{\text{in}}^4 \quad , \quad (3)$$

where σ is the Stefan-Boltzmann constant. This model function is simple, and well reproduces the soft spectral component of high/soft state black hole binaries with physically meaningful fit parameters. For example, the soft component of Cyg X-1 shown in Fig. 1 was well fitted with the MCD model of $R_{\text{in}} = 90$ km (Dotani et al. 1997) with $\kappa = 1.7$ and $\xi = 0.41$. Since the black hole mass of Cyg X-1 was estimated to be $10\text{--}16 M_{\odot}$ from several optical observations (Gies & Bolton 1986, Ninkov et al. 1987, Liang & Nolan 1983), the last Keplerian orbit, R_{ms} , of a non-spinning black hole is calculated as $R_{\text{ms}} = 6R_g (= 6GM/c^2) = 89\text{--}140$ km for Cyg X-1. Therefore, it is found that R_{in} determined by the X-ray observations well agrees with R_{ms} calculated by referring to the optical observations.

Even more compelling evidence for the standard disk formalism is given by the observational fact that the value of R_{in} is usually observed to remain constant in the high/soft state as L_{disk} changes significantly. This indicates that R_{in} reflects the physical parameters of the black hole itself. Figure 2 shows the values of L_{disk} obtained by spectral fits of ~ 80 RXTE/PCA observations of high/soft state spectra from LMC X-3, a well known black hole binary system. This figure shows that all the data points lie along the solid line which represents $L_{\text{disk}} \propto T_{\text{in}}^4$ (requiring constant emitting area i.e. constant r_{in} , and constant colour temperature correction, κ , in equation 3) over the range of $L_{\text{disk}} = 1\text{--}8 \times 10^{38}$ erg s $^{-1}$ ($\sim 10\text{--}80\%$ of the Eddington limit, L_{E} , of a $6 M_{\odot}$ black hole).

This relation of $L_{\text{disk}} \propto T_{\text{in}}^4$ has been widely observed in many high/soft-state black hole binaries except at very high disk temperature (typically at $> 0.9\text{--}1.2$ keV, see below). (e.g., Tanaka & Lewin 1995; McClintock & Remillard 2003; Ebisawa et al. 1994; Gierlinski & Done 2004).

Despite these successes, standard disc models strongly conflict with the observed disc emission on several points. (1) The α viscosity parameterisation of the standard Shakura-Sunyaev disc model is unstable in the range $\sim 0.1\text{--}1$

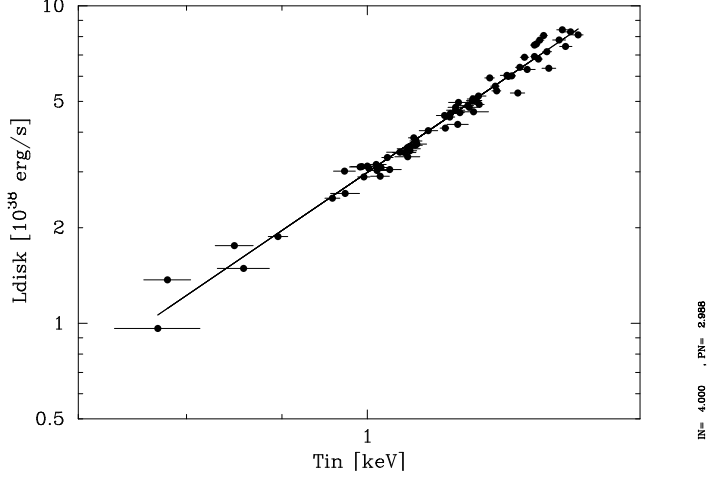


Fig. 2. The estimated L_{disk} of LMC X-3 are plotted against the observed T_{in} . The source distance and inclination are assumed to be $D = 50$ kpc and $i = 66^\circ$. The solid line indicates $L_{\text{disk}} \propto T_{\text{in}}^4$.

L_E where radiation pressure is dominant but the disc is not yet optically thick enough to regain stability through advecting the radiation (slim disk solution; Abramowicz et al. 1988). Yet the observed disk emission is very stable in this luminosity range. (2) Theoretical models of radiation transfer through the disc vertical predict that the colour temperature correction factor should change with luminosity. However, the amount of this change has now been shown to be rather small when true metal opacities are included (Davis et al 2005). This superceeds previous work which included only H and He, where the calculations of Merloni et al (2000) predicting a large change in κ , while those of Shimura & Takahara (1995) had κ varying by less than 20%. The resolution of this discrepancy may be that Merloni et al (2000) assumed a vertical density profile which is appropriate for a radiation pressure dominated disc, but their lowest luminosity discs are gas pressure dominated (Gierlinski & Done 2004).

Thus while the second point is now not necessarily in conflict with the standard disk models, the stability of the observed high/soft state spectra can give constraints on theoretical models of accretion disc structures.

2 Breakdown of the standard disk

However, high L/L_{Edd} spectra are not always disk dominated. There is an alternative bright spectral state, termed "very high" or "steep power law" state which was discovered by Miyamoto et al. (1991) and is characterised by both strong disk *and* strong (and rather steep) power law emission which is highly variable (e.g. van der Klis 1994; McClintock & Remillard 2004). When the spectra in this state are fitted with the canonical MCD plus power-law model, the data no longer show $L \propto T^4$, implying that the estimated values

of R_{in} (and/or the colour temperature correction, κ) are no longer constant. This anomalous behavior is clearly seen in Fig. 3 which shows results of the MCD plus power-law fit to the PCA data of two high state black hole binaries, GRO J1655 – 40 and XTE J1550 – 564 (Kubota, Makishima, Ebisawa 2001, KME01; Kubota & Makishima 2004, KM04). The data points indicated with open circles show significant variation in both T_{in} and R_{in} , while those with filled circles show constant values of R_{in} . This anomaly was found when the spectra have a strong power law tail, carrying more than ~ 30 per cent of the luminosity (corresponding to a hardness ratio larger than ~ 0.6 – 0.7 shown in the top panels of Fig. 3).

Another breakdown in the $L_{\text{disk}} \propto T^4$ relation can also be seen in Fig. 3 for highly luminous *disk dominated* spectra with negligible power-law tail (filled squares: details are in KME01 and KM04). However, the obtained values of R_{in} are slightly (but systematically; ~ 15 – 25% in GRO J1655 – 40 and ~ 10 – 15% in XTE J1550 – 564) smaller than those in the typical high/soft state indicated with filled circles in Fig. 3.

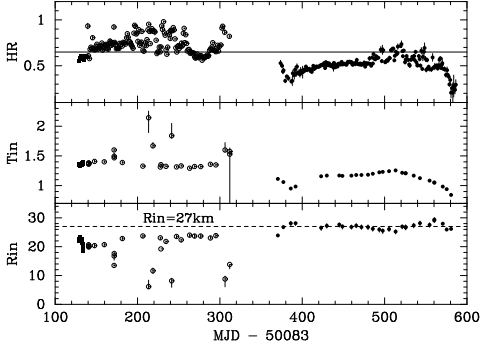
These violations can be characterized in Fig. 4 in which L_{disk} is plotted against T_{in} . In this figure, data points with filled circle are consistent with solid lines showing constant R_{in} via equation (3), and thus they are in good agreement with the standard picture as is the case of LMC X-3. We thus called these data points standard regime in KME01 and KM04. On the other hand, the data points with open circles, show significant deviation from the solid lines in both GRO J1655 – 40 and XTE J1550 – 564, so were termed anomalous regime by KME01 and KM04, or "weak very high state" by Kubota & Done (2004). The data points with filled squares show the highest L_{disk} . Their deviation is much milder than that of the anomalous regime, and their spectral shape is similar to that of the standard regime. This was termed "apparently standard regime" by KM04. Figure 5 shows examples of typical PCA spectra of XTE J1550–564 in each regime.

3 Understanding the observed problems

3.1 Inverse Compton scattering in the anomalous (weak very high) regime

A clue to the problem in the anomalous regime was given by KME01 and KM04. They showed that the anomalous regime was seen when there was enhanced hard X-ray power law emission compared to the disc dominated spectra. This shows that there is significant inverse Compton scattering of the disk photons by some high energy electrons, probably in a corona over the disk. The spectral shape requires that the Compton region is mildly optically

(a) GRO J1655-40



(b) XTE J1550-564

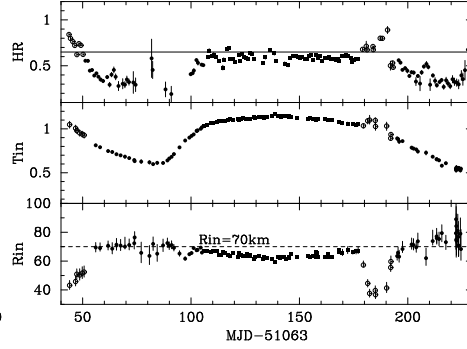
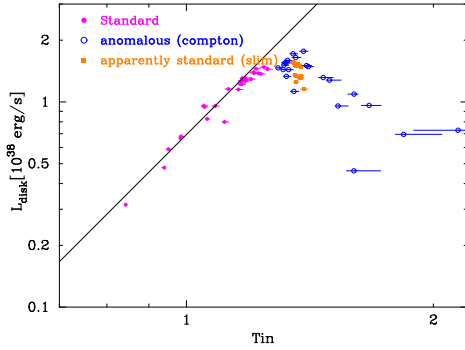


Fig. 3. Hardness ratio (5–12keV/3–5keV) by the RXTE/ASM and values of T_{in} and R_{in} obtained by the MCD plus power-law fit to the RXTE/PCA data of GRO J1655–40 (a) and XTE J1550–564 (b). Filled circle, open circle, and filled square indicate the standard regime (standard disk), the anomalous regime (very high state; strong comptonization), and the apparently standard regime (slim disk), respectively. These are taken after KME01 and KM04.

(a) GRO J1655-40



(b) XTE J1550-564

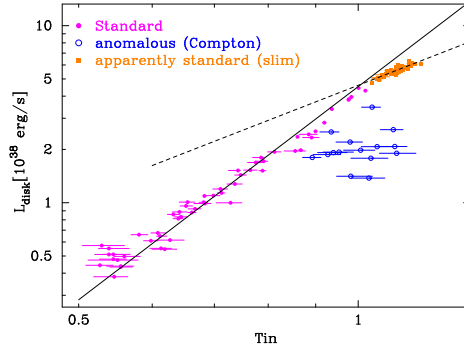


Fig. 4. L_{disk} is plotted against T_{in} based on the MCD plus power-law fit (after KME01 and KM04)

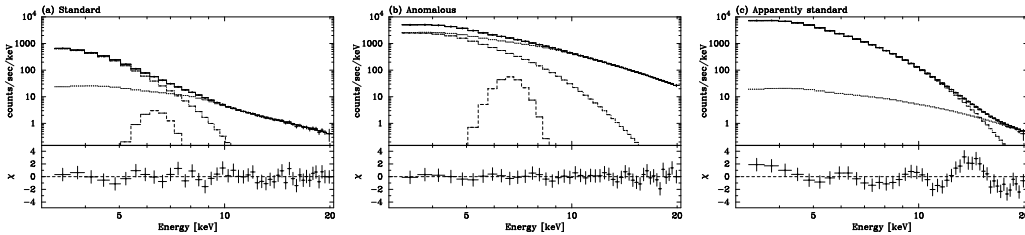


Fig. 5. Typical PCA spectra of XTE J1550–564 fitted with the MCD plus power-law model. The results of the standard regime (a), anomalous regime (b) and apparently standard regime (c) are shown after KM04. Note how the power law contribution is small in the standard and apparently standard regimes, but is much larger in the anomalous spectrum.

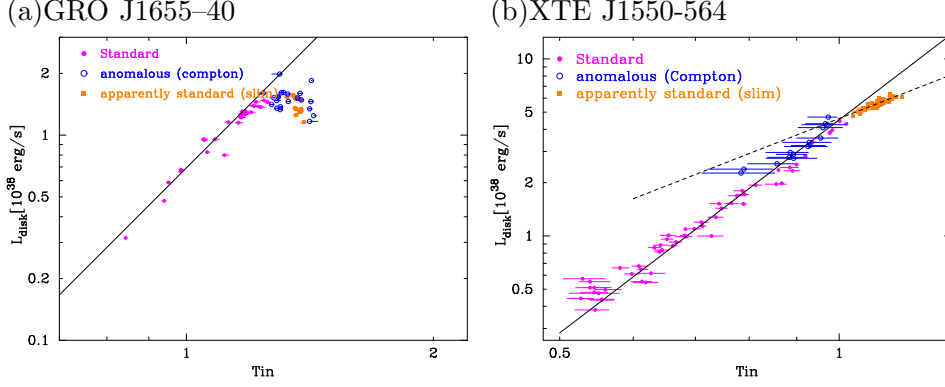


Fig. 6. $L_{\text{disk}} + L_{\text{comp}}$ is plotted against T_{in} based on MCD plus power-law plus Compton component fit (after KME01 and KM04).

thick, so the disk luminosity is artificially suppressed by $\sim e^{-\tau}$. In Fig. 6 we approximately correct for this by plotting $L_{\text{disk}} + L_{\text{thc}}$ (L_{thc} is the bolometric luminosity of the thermal Compton component) instead of L_{disk} , against T_{in} based on this spectral fits. We found that the anomalous regime points in Fig. 4 settled back to the solid line, consistent with a constant inner radius disk in this and the disk dominated states. Other approximations for the correction to the observed disk luminosity (e.g. assuming that Compton scattering conserves photon number) give similar results (KM04).

A mildly optically thick, thermal inverse Compton scattering is generically required in all broad bandpass data of the very high state (GS 2000+25, GS 1124-68: Zycki, Done & Smith 1999; XTE J1915+105: Zdziarski et al 2002; XTE J1550-564, Gierlinski & Done 2003; GRO J1655 - 40: Kobayashi et al. 2003).

It is interesting to note here that QPOs are preferentially observed in the anomalous regime in both GRO J1655-40 (Remillard et al. 1999) and XTE J1550-564 (Remillard et al. 2002), and the energy spectra of the QPO are also follow the spectrum of the Comptonised emission. Therefore, the QPOs should have some relation to the existence of the Compton cloud.

3.2 Another cooling process in the apparently standard regime

The apparently standard regime corresponds to the most luminous phase of the outburst, and the data in this regime occupies the upper-right region of the $L_{\text{disk}}-T_{\text{in}}$ diagram (Fig. 6). As seen in Fig. 5, the spectra in the apparently standard regime show a dominant soft component accompanied by a very weak hard tail. Although these properties are similar to the standard regime, the apparently standard regime is slightly different from the standard regime because the disk luminosity does not increase with T^4 , but rather more slowly, more like T^2 . Thus either the disk inner radius is decreasing, or the colour

temperature correction is increasing (or both).

Moreover, KM04 showed that the canonical spectral model often failed to give acceptable fits to the data (Fig. 5; see also Fig. 2 in KM04). In order to quantify the difference, KM04 constructed a generalization of the MCD model in which the radial temperature dependance is $T(r) = T_{\text{in}} \cdot (r/r_{\text{in}})^{-p}$. This p -free disk model differs from the standard MCD model which has p fixed at $3/4$, so there are now three fit parameters, T_{in} , r_{in} , and p (see also Hirano et al. 1995, Mineshige et al. 1994).

In Fig. 7, the best fit values of p are plotted against T_{in} for LMC X-3, GRO J1655 – 40 and XTE J1550 – 564. Though the absolute values of p were slightly affected by fitting conditions (whether Γ or N_{H} were fixed or free, including (or excluding) a gaussian for a narrow iron line), the characteristic p - T_{in} behavior on Fig. 7 was not affected by them. As a calibration trace on p - T_{in} plane for the standard regime, we show a result of LMC X-3 in Fig. 7a. This source stays in the standard regime up to $\sim L_{\text{E}}$, and shows positive correlation between p and T_{in} . With the PCA data, this positive correlation is considered as an artifact which is present even if the standard accretion disk is realized. This artifact happens because the MCD model ignores the boundary condition at the inner edge of the standard disk solution. The actual temperature gradient of a standard accretion disk must be flatter than $3/4$ near the innermost disk edge, where the temperature will approach zero. As T_{in} decreases, the limited PCA band pass will sample preferentially the emission from inner disk regions, thus making p appear smaller than $3/4$ as is found in LMC X-3.

As for XTE J1550 – 564, while the data points for $T_{\text{in}} \leq 1\text{keV}$ (standard regime) are well consistent with the calibrated trace in Fig. 7c, those for $T_{\text{in}} \geq 1\text{ keV}$ (in the apparently standard regime) appear well below the trace (and in fact, p *negatively* correlates to T_{in}). Similarly, the data points of GRO J1655 – 40 for $T_{\text{in}} \leq 1\text{--}1.1\text{ keV}$ are mostly consistent with the trace, but those for $T_{\text{in}} \geq 1.1\text{ keV}$ are below the trace. Therefore, the observed temperature gradient in the apparently standard regime is smaller than in the standard regime.

This result means that the radiative efficiency at the inner portion of the accretion disk in the apparently standard regime is lower than that in the standard regime (case of the standard disk). Hence the accretion disk in the apparently standard regime deviates from the standard disk and requires another cooling process in addition to radiative cooling. The advection in the optically thick disk is a candidate for the cooling process, and in fact, the slim disk solution, seen in a top slope of the S -shape sequence (Abramowicz et al. 1995), predicts smaller values of p than the standard disk (e.g., Watarai et al. 2000).

3.3 Brief summary of the obtained picture

We show that there are three spectral regimes in the stable high/soft state black hole binaries, the standard regime, the anomalous (weak very high) regime, and the apparently standard regime. The last two regimes appear typically when the X-ray luminosity exceeds a certain critical luminosity. The accretion disk structures are somewhat different in these three regimes, but all are consistent with the disk extending down to a constant inner radius, most probably the innermost stable Keplerian orbit around the central black hole. The accretion disk in each regime is characterized by a radiation dominated standard disk but in the anomolous regime there is also high energy plasma which causes the observed strong Compton scattering, while in the apparently standard regime there is some change to the cooling process, perhaps marking the onset of advection cooling in addition to radiative cooling. This picture can also explain many other black hole binaries in the high accretion rate state including 4U 1630 – 47 (Abe et al. 2004).

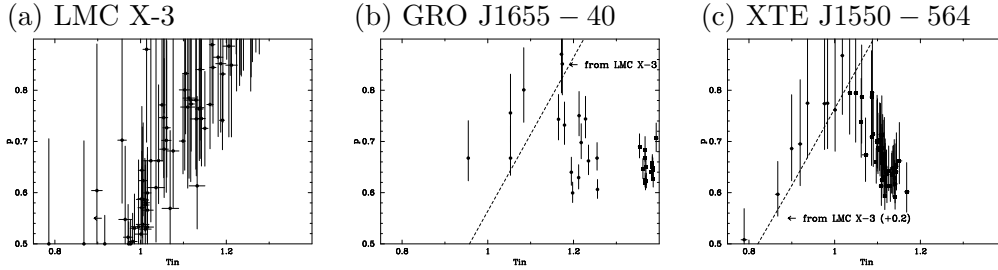


Fig. 7. The best fit values of p against T_{in} of LMC X-3 (a), GRO J1655 – 40 (b), and XTE J1550 – 564 (c). Instead of the values of T_{in} obtained by the p -free disk model, those by the MCD model are employed, in order to avoid any systematic coupling between p and T_{in} . Dashed lines show the calibrated trace of p obtained with the LMC X-3 (a). The absolute value of p includes PCA systematic effects, and the calibrated line in panel (c) is obtained by shifting the result of LMC X-3 as $\Delta p = +0.2$.

4 Analogy to ULXs

Based on their X-ray luminosities, ultraluminous compact X-ray sources (ULXs) in nearby galaxies are supposed to be intermediate mass ($\sim 30\text{--}100 M_{\odot}$) black holes (Makishima et al. 2000), super Eddington stellar mass black holes, or (mild) beaming black holes (e.g., King et al. 2001). Among many ULXs, Mizuno et al. (2001) analyzed three bright ($0.2\text{--}1.5 \times 10^{40} \text{ erg s}^{-1}$) variable ULXs observed with ASCA, IC 342 source 1, M81 X-6 (sometimes called X-11) and NGC 1313 source B. They found that the X-ray spectra are well reproduced by the MCD model and that obtained values of R_{in} are not constant but variable as $R_{\text{in}} \propto T_{\text{in}}^{-1}$. This is very similar to that of XTE J1550 – 564 in

the apparently standard regime. In addition, Kubota et al. (2002) analyzed the other spectral data of IC 342 source 1 obtained with ASCA in different date. During that observation, the source showed a power-law like spectrum rather than the MCD shape, and it was reanalyzed in the framework of the inverse comptonization as is the case of the anomalous regime. They found that this power-law like spectrum then lies nicely on the same luminosity-temperature relation as defined by the MCD-type spectra given by Mizuno et al. (2001).

We can see that the data points of bright ULXs on $T_{\text{in}}-L_{\text{disk}}$ diagram is understood by shifting up those of stellar black hole, XTE J1550 – 564 in the brightest regimes (see Fig. 2 by Kubota et al. 2002). These spectral studies thus supports the scenario of high accreting relatively massive (more massive than Galactic stellar black holes) black holes for ULXs.

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